Study on Rheological Properties of Partially Hydrolyzed Polyacrylamide Solution at Elevated Temperature

by

Dharveen Kumar

Dissertation submitted in partial fulfillment

of the requirements for the

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(CHEMICAL ENGINEERING)

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Universiti Teknologi PETRONAS

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CERTIFICATION OF APPROVAL

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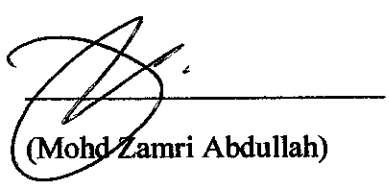
Approved by,



(Mohd Zamri Abdullah)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

JANUARY 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken by unspecified sources or persons.

DHARVEEN KUMAR

ABSTRACT

Rheology is the science of flow and deformation of matter primarily liquid, but also solid under certain conditions in which they respond with plastic flow rather than deforming elastically in response to an applied force. It applies to substances which have a complex molecular structure such as mud, sludge and polymer which are also examples of non-Newtonian fluids. The flow of these substances cannot be characterized by a single value of viscosity (at a fixed temperature or pressure). Although it is proven that viscosity of fluids normally varies with temperature, other factors which lead to different viscosity trend are also studied in rheology. Partially hydrolyzed polyacrylamide is a polymer which is widely being used by drilling fluid companies in oil and gas industry as their primary viscosifier in water based mud system. Plus, its ability to encapsulate the drill cuttings (shale) from the hydration of fluid (water) from the mud or the formation classifies it as the most important inhibitor in water based mud system. While it is being widely used, the ability of partially hydrolyzed polyacrylamide to perform under high pressure and high temperature condition is still not clearly known. Thus, this study is aimed at investigating the rheological behavior of partially hydrolyzed polyacrylamide solution at normal pressure and elevated temperature as a starting point to the rheological study of partially hydrolyzed polyacrylamide under high pressure and high temperature condition.

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NOMENCLATURE

k	=	consistency index, $Pa.s^n$
M_1	=	concentration of master solution, ppm
M_2	=	concentration of dilute solution, ppm
n	=	flow behavior index
V_1	=	volume of master solution, ml
V_2	=	volume of dilute solution, ml
μ	=	viscosity, Pa.s or cP
γ	=	shear rate, 1/sec
τ	=	shear stress, Pa

CHAPTER 1: INTRODUCTION

1.1 Background of Study

Water soluble polymers are rapidly growing practical importance as viscosity-enhancing agents, flocculating agents, food additives, etc. (Munk et al., 1980). Polyacrylamide (PAAM) is one of the water-soluble polymers which is a non-toxic polymer formed from acrylamide subunits which can be synthesized as a simple linear-chain structure or cross-linked.

Partially hydrolyzed polyacrylamide (HPAM), an enhanced version of PAAM solution is being widely used currently. It plays an important role in water treatment as an anionic coagulant, as a viscosifier and shale stabilizer in drilling mud and in enhanced oil recovery (EOR), where it is used as pushing fluid in the injection wells to sweep the oil from reservoir into production well.(Zeynali, 2004)

Due to its wide usage and further enhancement, various studies have been conducted on the behavior of HPAM. The effect of temperature and concentration on rhelogical properties have been studied in applications such as making clarified juice solution but only a few reports are available on the effect of various temperature and concentration. (Yang & Yen, 2001)

Many experimental studies have been carried out by researchers such as Munk et al. (1980), Kulicke et al.(1982), Ghannam (1998), Yang & Yen (2001) and Zhang et al.(2008) but none of them have tested HPAM under elevated temperature condition. Thus, the scope of this research will be under the stated condition.

1.2 Problem Statement

Partially hydrolyzed polyacrylamide is an important additive used to enhance the viscosity of water based drilling mud. Although HPAM is widely used in oil industry, it is unknown whether the properties will change due to elevated temperature condition, thus this project is being carried out to investigate the rheological behavior of HPAM under elevated temperature and normal pressure condition.

1.3 Objective

The main objective of this research is to investigate the effect of elevated temperature and normal pressure on the viscosity trend, shear rate and shear stress.

1.4 Scope of Study

Six different parameters have been chosen to conduct the study. A constant master solution concentration, hydration period and pressure will be used throughout the experiment to compare the results of each study that will be carried out. The scope of the study will be on the viscosity trend of HPAM at a constant hydration period, pressure, and master concentration, two different elevated temperatures, five different dilute concentrations and various shear rates.

1.4.1 The relevancy of the Project

In this project we will be focusing on rheological properties at elevated temperature and normal pressure conditions. It will be highly beneficial for the drilling fluid companies around the world which are still investigating until which extend does HPAM can operate as viscosifier in water based mud system. Furthermore, the result of this project will be a stepping stone for drilling fluid companies to try operating with water based mud system under elevated temperature conditions. Plus, water based mud system is environmental friendly and cheaper compared to oil based mud system.

CHAPTER 2: LITERATURE REVIEW & THEORY

2.1 Literature Review

Nowadays partially hydrolyzed polyacrylamide is gaining more scientific interest from the researchers around the world due to its wide usage in various industries and commercial application, especially in oil industry. "The viscosity of hydrogel, which is produced by a dilute or semidilute HPAM solution cross-linked with cross linker, is higher than that of non-crosslinked HPAM solution of same concentration". (Zhang et al. 2008) Thus it means that HPAM acts as the most suitable substance to be used as the sweeping fluid to further recover the oil in the reservoir after the first stage of production.

It is said that the viscosity varies significantly depending on certain parameters such as temperature, pressure, concentration and etc. A lot of studies have been carried out to determine the behavior of HPAM under these circumstances. "The effects of solvent, salt type and concentration, degree of hydrolysis, and polymer concentration on viscosity have been investigated. It was shown that the reduced viscosity of salt-free solution of partially hydrolyzed polyacrylamide as a result of polymer chain expansion increases with decreasing polymer concentration".(Zeynali et al. 2004)

These particular parameters does not only determines the viscosity of the solution but do also play a role in determining whether the polymer solution shows shear thinning or shear thickening effect with increasing shear rate. "The shear thickening behavior of HPAM is observed at relatively low polymer concentration and at very high shear rate. At very low concentration of polymer, a slight increase in polymer concentration will cause the critical value of shear rate to be shifted to higher shear rate". (Lewandowska, 2006). Thus, it concludes that HPAM does not only experiences shear thinning behavior but it also has the potential to behave as a shear thickening polymer.

Further models and correlations have been invented to prove the behavior of HPAM in order to extend its usage purposes. "By devising the mathematical model for the rheological behavior of PAAM solution, which relates yield stress at various temperatures and concentration, it can be proven that, at higher concentrations of PAAM solution leads to increment in the shear stress. When the concentration is fixed and the temperature is varied, the shear stress decreases with increasing temperature. Furthermore it has been concluded that PAAM solution has a non-Newtonian fluid characteristic and its yield stress decreases with increasing temperature". (Yang and Yen, 2001) Thus, it proves that rheological studies are very important in determining the exact behavior of HPAM under various conditions.

2.2 Theory

2.2.1 Partially Hydrolyzed Polyacrylamide (HPAM)

Partially hydrolyzed polyacrylamide is a very important substance in the oil and gas industry as it plays different functions in different type of usage. In the drilling fluid, HPAM is used as viscosifier due to its long chain high molecular weight polymer plus it has its secondary function as encapsulating agent which inhibits the drilling cuttings and also the clay from swelling due to hydration caused by formation fluid and also the fluid in the drilling fluid itself.

HPAM is formed from a copolymerization process between acrylamide and sodium acrylate and available in two different categories. One the long chain high molecular weight polymer and the other is short chain low molecular weight polymer. These two polymers have their different applications, advantages and disadvantages. Low molecular weight polymer has a low viscosity impact on the mud properties plus, absorption of low molecular weight polymer creates an overall negative charge resulting in deflocculation. On the other hand, high molecular weight polymer has a high viscosity impact on the mud properties and it acts as a bridge between the particles to form larger aggregates which will result in easier and better transportation of drill cuttings to the surface.

Long chain high molecular weight HPAM naturally appears in a coiled form when it is unhydrated. It will start to uncoil when being hydrated in a low salinity environment which will also allow it to form a long chain but if it is being hydrated in a high salinity environment it will uncoil and shrink due to the increase in salinity level. From the field experiment that has been carried out thus far, it has been proven that high temperature can cause HPAM to stretch which will progressively break down the polymer chain. The long chain can also break down due to the recirculation process while drilling and also to the rotational motion of the drill bit.

HPAM is a negatively charged high molecular weight which adsorbs onto the positively charged sites on the broken edge of the clay cuttings. This action results in the formation of a jelly like protective coating which plugs and seals shale pores retarding the movement of water into the shale. The protective coating of HPAM plays a significant role in strengthening the surface of the shale so that it better withstands the effects of mechanical abrasion or attrition leading to dispersion of clay into the mud which will disrupt the rheological properties of the mud

2.2.2 Rheology

Rheology is derived from the Greek words *rheo*, meaning flow and *logi*, meaning science. It can be defined as the science of the deformation and/or flow of solids, liquids and gases under applied stress. In essence, the science deals with the stress-strain-time relationships of any matter.

The rhological characteristics of material form a continuous spectrum of behavior ranging from that of the perfectly elastic solid at one extreme to that of the purely viscous Newtonian fluid at the other. Between there extremes lies the behavior of fluids which possess varying degrees of character of both extreme materials, such as materials are termed visco-elastic.

The science is still in its infancy in terms of the ability to provide accurate predictions of the behavior of real systems. This is particularly true with regard to polymer additive muds being used in drilling operation today, which have far complex behavior than true fluid.

Despite this, it is still common practice to express flow characteristics in terms of simple viscosity terms such as the constants used in the Bingham Plastic and Power Law models. Certain basic concepts of rheology require to be understood to make optimum use of collected data. Of these concepts the relationship between shear stress and shear rate is most important in predicting polymer behavior

2.2.3 Shear rate

In a moving fluid shear rate can be defined as the rate at which one layer of fluid is moving by another layer divided by the distance between the layers. It is the velocity gradient in example, the ration of velocity to distance between layers.

Consider a fluid between two flat plates one centimeter apart. If the bottom plate is fixed while the top plate slides parallel to it at a constant velocity of 1 cm per sec, a velocity profile will be found within the fluid. The fluid layer in contact with the bottom plate is static while the layer in contact with the top plate is moving at 1 cm per sec. Halfway between the plates the fluid velocity is the average 0.5 per sec.

If a moving layer of fluid has a velocity 1cm/sec relative to static layer at separation distance of 1 cm then the shear rate between these layers will be:

$$\frac{1\ cm/sec}{1\ cm} = 1\ sec^{-1}$$

The reciprocal second is the standard unit of shear.

2.2.4 Shear stress

Shear stress is defined as the force required to move a given area of the fluid. In this case one Newton is required for each square meter of area. The units of shear stress are Newtons per square meter, also known as Pascals. Alternative unit for shear stress are dynes per square centimeter and pounds force per square inch. Shear stress is related to the force required to sustain fluid flow.

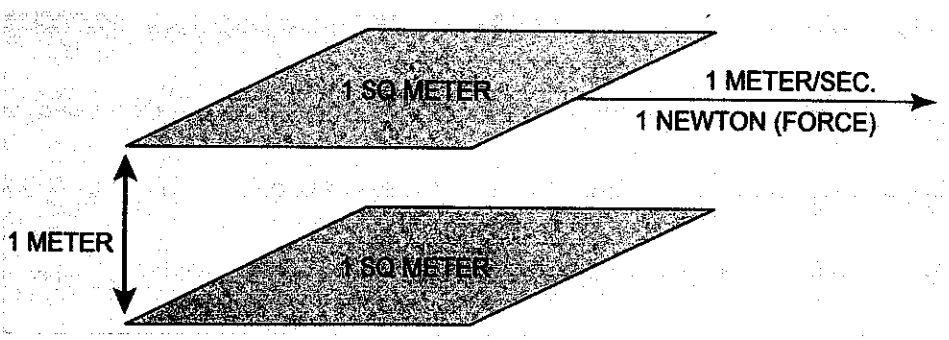

Figure 1: Forces acting on a theoretical liquid

Figure 1 shows the forces acting on a theoretical liquid. The liquid is contained between the two 1 square meter plates which are separated by one meter. The bottom plate is stationary and the top plate is moved at a rate of 1 meter per second. The amount of force required to maintain this movement is measured in Newtons.

A force of 1.0 dyne was applied to each square meter of the top plate to keep it moving. Then the shear stress would be 1.0 dyne per cm^2. The same force in the opposite direction would be needed on the bottom plate to keep it from moving. The same shear stress would be found at any level in the fluid. Shear stress is constant only as long as the flow system geometry is constant. It is

more common to find the shear stress varying from one part of a flow system to another.

The units of shear stress are the same as for pressure, but whereas pressure defines the applied force per unit area, shear stress is the internal resistance to an applied stress.

Shear stress can be expressed:

$$\text{Shear stress} = F/A$$

Where F = Force

A = Area of surface subject to stress

The standard unit of shear stress is dynes/cm^2.

2.2.5 Viscosity

Viscosity can be described as the resistance to flow and is defined as the ration of shear stress and shear rate

$$Viscosity = \frac{shear\ stress, (dynes/cm^2)}{shear\ rate, (sec^{-1})} = Poise$$

The units of Poise are too large for rheology studies thus, it is usually reported in centipoises, cP or milipascal.second, mPa.s

Since viscosity is dependent on both shear rate and shear stress, one or the other must be specified when a viscosity measurement is stated. Shear rate is the usual variable defined, either as an actual shear rate in reciprocal seconds or as speed in rpm from a concentric cylinder viscometer.

2.2.6 Fluid models

Fluids can be separated into different classes according to the relationships which exists in a fluid between shear rate and shear stress. The most simple class of fluids are called Newtonian. Water and light oils are examples of Newtonian fluids.

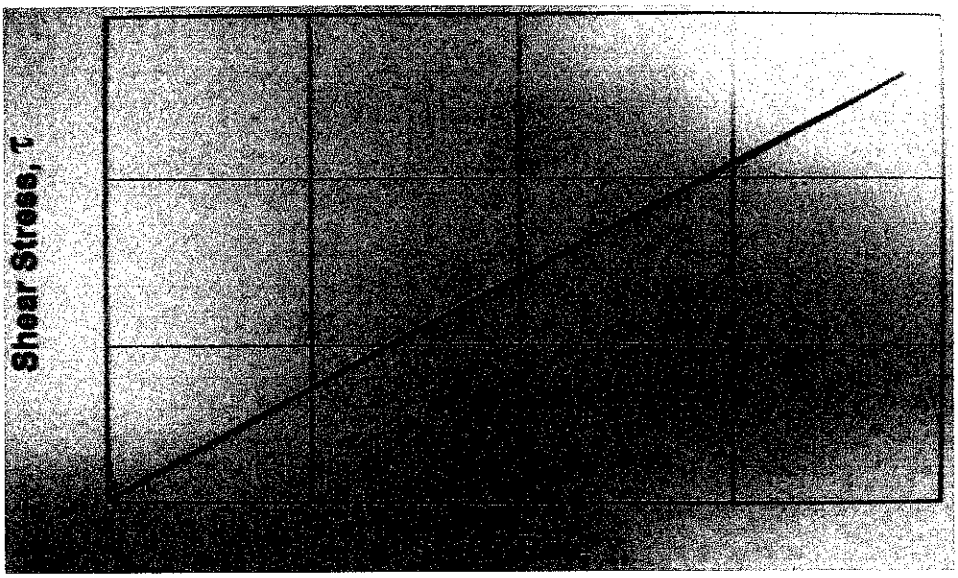

Figure 2: Newtonian fluid behavior

In these fluids shear stress is directly proportional to the shear rate. When the shear rate is doubled the shear stress is also doubled. Such fluids have a constant viscosity.

For most fluids, viscosity is not a constant, but varies with the shear rate. Such non Newtonian fluids are called rate dependent. Almost all polymer solution which is used as viscosifier in the drilling mud provide rate dependent fluids.

To illustrate rate dependent effects a fluid is tested for shear stress or viscosity at a number of shear rates. When these data are plotted on a log-log scale a viscosity profile of the fluid is obtained. Examples of types of flow are shown in Figure 3.

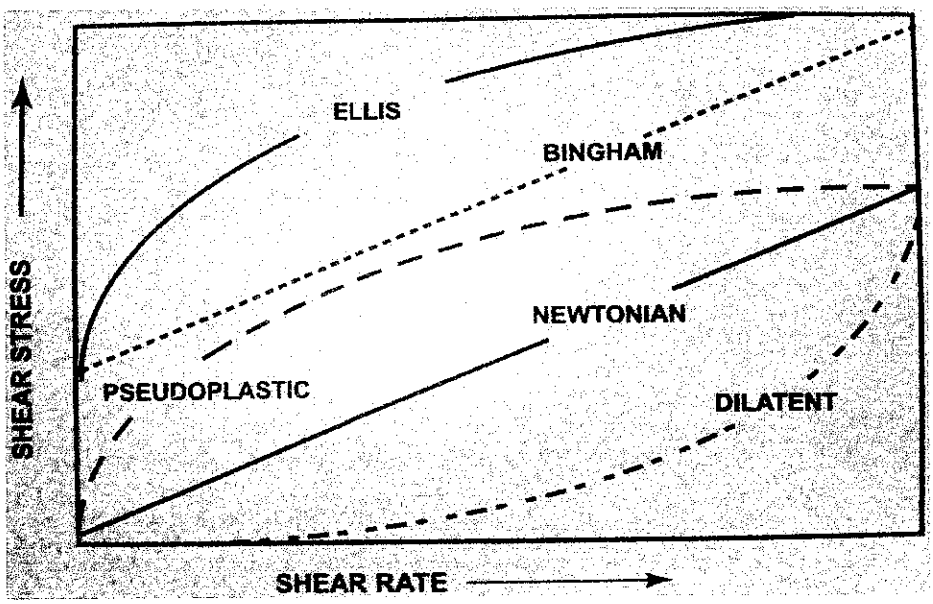

Figure 3: Types of flow

The shear rate / shear stress ratio of non Newtonian fluids are not constant, which is true of most polymer solutions. Three most popular mathematical models for describing non Newtonian polymer solution are called the Bingham Plastic model, Power Law model and modified Power Law or Herschel-Bulkly model.

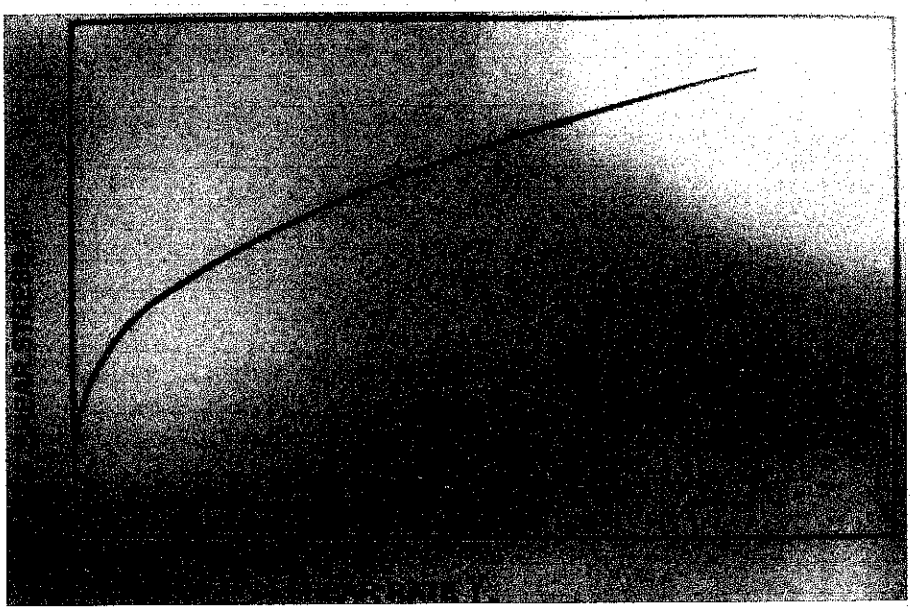

Figure 4: Non Newtonian fluid behavior

Some fluids have a critical yield stress which must be exceeded before flow is initiated. If the fluid has essentially Newtonian flow after the yield stress is exceeded it is termed as Bingham Plastic fluid.

Bingham Plastic model, $\tau = \tau_y + \mu_p (\gamma)$

Where, τ = shear stress, Pa

γ = shear rate, sec^{-1}

τ_y = yield point, Pa

μ_p = plastic viscosity, Pa.sec

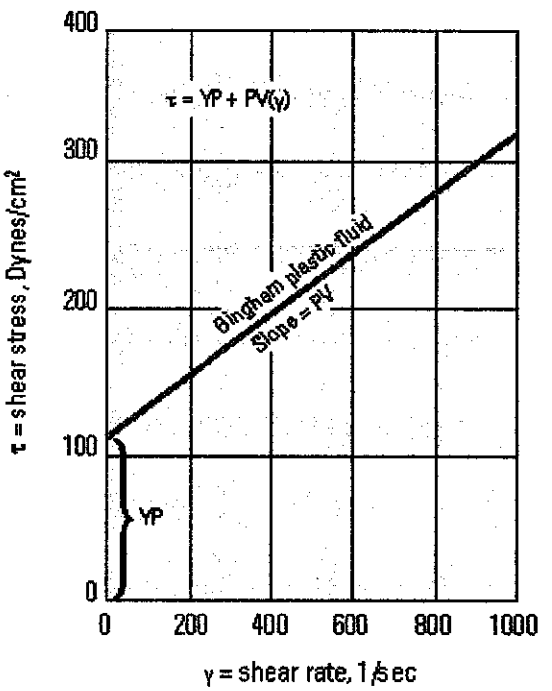

Figure 5: Shear stress vs shear rate plot for Bingham Plastic fluid

Most polymer solutions are Pseudoplastic. Materials that exhibit shear-thinning can be classified as either Pseudoplastic. In this case, increased shear rate produces a progressive decrease in viscosity. In polymer solutions, this is

due to the alignment of the long polymer chains along the flow lines. If the application of any shear stress above zero produces fluid flow, in example, no critical yield stress, the fluid is termed as Power Law fluid. This model more accurately describes flow characteristics of polymer solutions over the shear rate ranges experienced in the annulus of a well bore.

Power Law model, $\tau = K(\gamma)^n$

Where, τ = shear stress, Pa

γ = shear rate, sec^{-1}

K = consistency index, $Pa.sec^n$

n = flow behavior index, (dimensionless)

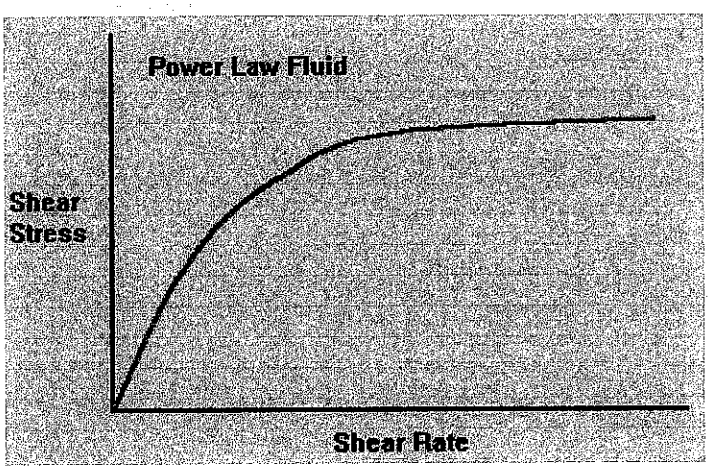

Figure 6: Shear stress vs shear rate plot for Power Law fluid

Although the API has selected the Power Law model as the standard model, the Power Law model, however, does not fully describe polymer solutions because it does not have a yield stress and underestimates low shear rate viscosity. The modified Power Law or Herschel-Bulkly model can be used to account for the stress required to initiate fluid movement.

Modified Power Law, $\tau = \tau_y + K\gamma^n$

Where, τ = shear stress, Pa

γ = shear rate, sec^{-1}

K = consistency index, $Pa.sec^n$

n = flow behavior index, (dimensionless)

τ_y = yield point, Pa

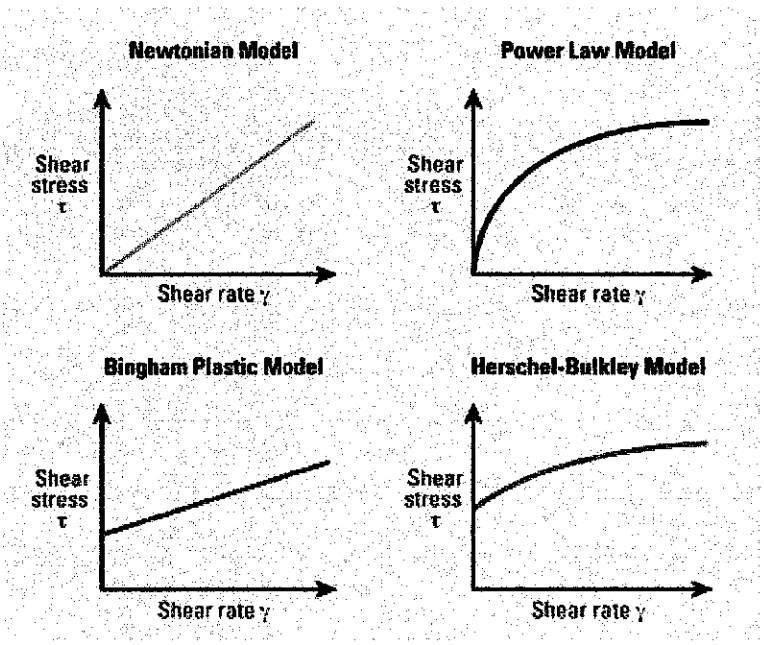

Figure 7: Shear stress vs shear rate plot for various rheology models

Although the modified Power Law is a slightly more complicated model than either the Bingham Plastic model or the Power Law, it can approximate more closely the true rheological behavior of most polymer solutions.

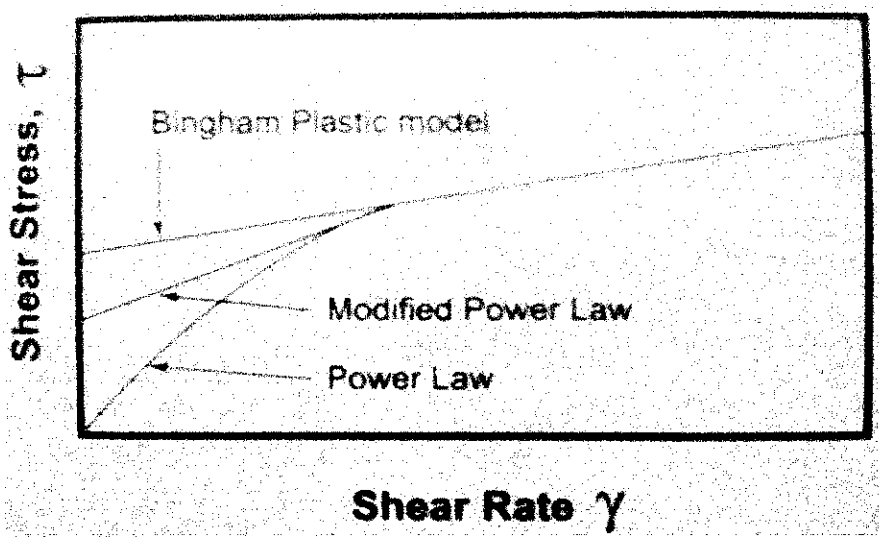

Figure 8: Differences between three different fluid models

Figure 8 shows the differences between the modified Power Law, the Power Law, and Bingjam Plastic models. The modified Power Law falls between the Bingham Plastic model, which is the highest, and the Power Law, which is the lowest and consequently more closely resembles the flow profile of a typical polymer solution.

2.2.7 Flow behavior index, *n*

The *n* constant indicates the degree of non Newtonian character that a fluid exhibits over a defined shear rate range. Newtonian fluids have *n* value of equal to one. As *n* decreases from one, the fluid becomes more Pseudoplastic or shear thinning with increase in shear rate.

The *n* constant is dependent upon the type of polymer used. Every material has an inherent *n* constant, but it may vary with concentration and shear rate.

2.2.8 Consistency index, *k*

K is the consistency index when the shear stress or viscosity of the fluid at a shear rate of one sec^{-1}. It relates directly to the system viscosity at low shear rates. The *k* constant is controlled by both the type of polymer and the total solids content of the fluid. It will increase with decrease in *n* constant or by increase in solid concentration. *K* can be reported as $Pa.sec^n$.

CHAPTER 3: METHODOLOGY

3.1 Research Methodology & Project Activities

Different findings and methodologies are gathered from the research work of other researchers and to be incorporated in this project. First and foremost, various journals and technical papers were read through the get the general understanding on the project. It is also needed to identify the objective of this project and to come up with a proven method to run the experiment. Once the objective has been identified, the proven method to prepare the solution is obtained with a series of discussion with my supervisor and also with the reference from the previous works done by other researchers.

3.2 Polymer Solution Preparation

After series of discussion with my supervisor, we have come to a conclusion that to use his method of preparation which he has used for his Phd studies to prepare the polymer solution. In order to prepare 700 ppm of master solution, I will have to mix 7 grams of HPAM powder with 10 liters of distilled water. The HPAM powder will be sprinkled into the tank. Once it has been sprinkled evenly throughout the bottom of the tank, we will have to add 10 liters of distilled water at once to ensure perfect mixing. This mixture will be agitated using a stirrer (Brand: IKA, Model: EUROSTAR Power Control-Visc 2600000) at a constant rotating speed of 50 rpm for 2 hours before storing it at room temperature for 1 day to hydrate the solution. The analysis of the master solution is performed after 1 day hydration period is achieved.

Once 1 day of hydration period is achieved, the master solution will be further diluted to 10 ppm, 20 ppm, 30 ppm, 40 ppm, and 50 ppm solutions using distilled water, beaker and volumetric flask. This can be done by using the following equation:

$$M_1 . V_1 = M_2 . V_2$$

Where, M_1 = concentration of master solution (ppm)

V_1 = volume of master solution (ml)

M_2 = concentration of dilute solution (ppm)

V_2 = volume of dilute solution (ml)

Once the dilute solution has been prepared, it must be stored for a day to achieve the hydration period before being tested the following day.

3.3 Laboratory Testing

Once the hydration period is achieved, the rheological study will be conducted using the BROOKFIELD CAP 2000+ Viscometer (H Series) available at Solid and Waste Treatment Laboratory Block 5, Universiti Teknologi PETRONAS. The specification of this equipment is included in the table below:

Table 1: Specification of viscometer

Type	Sensitivity (%)	Viscosity Range (Poise)	Shear Rate (s^{-1})	Temperature (^0C)	Speed of Rotation (rpm)
Cone and Plate	0.01	0.2 – 15000	10 - 13000	50 - 235	5 - 1000

In the meantime, the temperature of 80^0C and 100^0C is used to see the effect of elevated temperature to the polymer solution. From the viscosity measurement, the properties such as consistency index, *k* and flow behavior index, *n*, and shear stress can be evaluated at different temperature using the best viscosity model.

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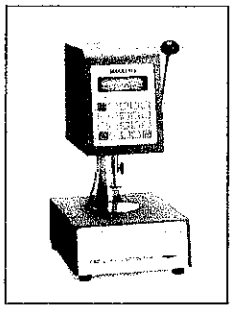

Figure 9: BROOKFIELD CAP 2000+ Viscometer

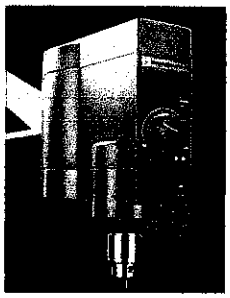

Figure 10: IKA EUROSTAR Power Control Stirrer

3.3.1 Methods of conducting the experiment

The experiment has been carried out in two different ways. It is to investigate which method gives the best reading in terms of viscosity reading and trend.

Method 1

The main principle of this method is using a new sample from the same sample bottle for each reading which will be taken at different shear rates using the viscometer. First the temperature of the viscometer will be set to the expected temperature which is 80^0C. Once the temperature is set, the spindle will be clamped down to ensure that the spindles temperature and the testing plate temperature are in equilibrium.

The shear rate will be set to the wanted shear rate, for an example 20 s^{-1} and few drops of the polymer solution will be placed on the testing plate. Once the temperature is constant at 80^0C the experiment will be started. Once the data is collected, the sample on the testing plate will be wiped and the shear rate will be changed to 30 s^{-1} before placing a new sample from the same sample bottle on to the testing plate.

These steps will be repeated until 3000 s^{-1} and the temperature will be increased to 100^0C. The whole steps will be repeated to gain the data for both temperatures.

Method 2

The second method focuses on using the same sample throughout the whole experiment at a specific temperature. First the temperature of the viscometer will be set to the expected temperature which is 80^0C. Once the temperature is set, the spindle will be clamped down to ensure that the spindles temperature and the testing plate temperature are in equilibrium.

The shear rate will be set to the wanted shear rate, for an example 20 s^{-1} and few drops of the polymer solution will be placed on the testing plate. Once the temperature is constant at 80^0C the experiment will be started. After jotting down the viscosity reading. The shear rate will be increased to 30 s^{-1} and the second run of data collection will be started. This particular step will be repeated until the viscosity reading for 3000 s^{-1} shear rate is taken.

Once the data for 80^0C is collected the temperature will be raised to 100^0C and the stated steps will be repeated to collect the viscosity reading.

3.4 Key Milestones & Gantt Chart

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Project Work Continues	■	■	■	■	■	■	■	Mid Semester Break								
2	Submission of Progress Report									★							
3	Project Work Continues									■	■	■	■	■			
4	Pre - SEDEX												★				
5	Submission of Draft Report													★			
6	Submission of Dissertation (soft bound)														★		
7	Submission of Technical Paper														★		
8	Oral Presentation															★	
9	Submission of Project Dissertation (Hard Bound)																★

■ Processes

★ Milestones

CHAPTER 4: RESULTS & DISCUSSION

4.1 Data Gathering, Analysis and Discussion

The viscosity test for both the master solution (700 ppm) and the dilute solutions was conducted at block 5 using the Brookfield Cap 2000+ Viscometer. The test is done using 6 different spindles and the best viscosity reading is taken from the spindle which gives the lowest percentage of error.

As has been stated in the previous chapter, spindle 6 is chosen as the best spindle to run the viscosity testing for both the master and dilute solutions. For each shear rate value, I have conducted the experiment twice which means two runs for each data in order to gain a accurate data. Following table shows the configuration of spindles available.

Table 2: Specification of spindles

Spindle	Shear Rate (s^{-1})	Sample volume (µl)	Cone Angle	Cone Radius (cm)	Viscosity 5 - 100 RPM (Poise)
1	13.3N	67	0.45°	1.511	0.2 - 375
2	13.3N	38	0.45°	1.200	0.4 - 750
3	13.3N	24	0.45°	0.953	0.8 - 1500
4	3.3N	134	1.8^0	1.200	1 – 3000
5	3.3N	67	1.8^0	0.953	3 - 6000
6	3.3N	30	1.8^0	0.702	8 - 15000

N = rpm

As we are aware, I have conducted the experiment in two different methods. The following tables and plots are the results for the rheology testing which has been conducted on 700 ppm master solution, 10 ppm, 20 ppm and 50 ppm dilutes solutions. Plus these are the data gathered by using the best spindle available which is spindle 6. The rest of the data has been attached in the appendices.

Table 3: Results for 10 ppm solution using method 1

10 ppm dilute solution						
Shear Rate (1/s)	Viscosity (cP)					
	80°C			100°C		
	1	2	% of error	1	2	% of error
107	4921.8	4931	0.186923483	4587.2	4612	0.54063481
200	0	0	-	782.4	804	2.760736196
307	4	7	75	0	0	-
400	44.1	53.2	20.63492063	78.3	82.3	5.108556833
507	0	0	-	425.7	423.5	0.516795866
600	542.6	539.6	0.552893476	257.4	248	3.651903652
707	78	85	8.974358974	459.9	460	0.021743857
800	324.5	320	1.386748844	338.2	344	1.714961561
907	243	248.3	2.181069959	287.3	278.54	3.049077619
1000	87	90	3.448275862	0	0	-
2000	0	0	-	887.5	880.2	0.822535211
3000	54	55	1.851851852	89.4	90	0.67114094

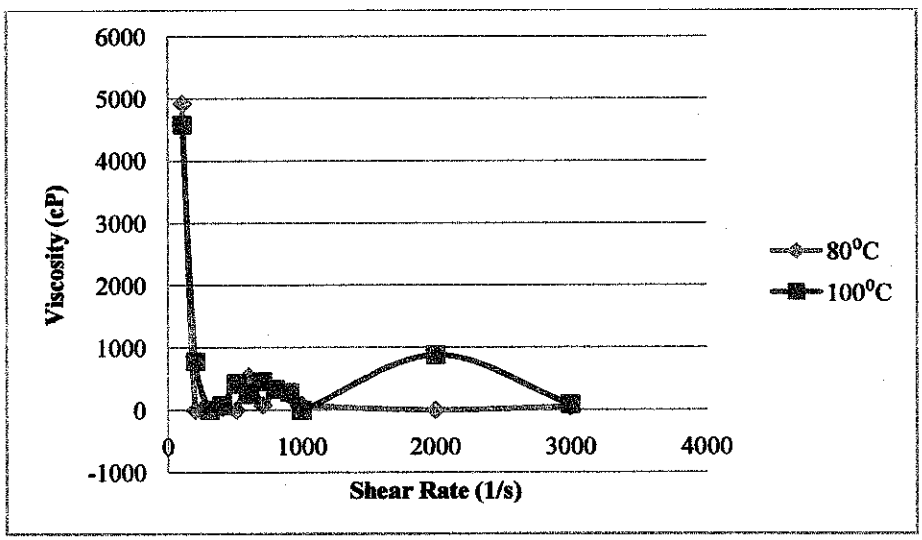

Figure 11: Viscosity trend of 10 ppm solution at 80^{0}C and 100^{0}C using Method 1

Table 4: Results for 20 ppm solution using method 1

20 ppm dilute solution						
Shear Rate (1/s)	Viscosity (cP)					
	80°C			100°C		
	1	2	% of error	1	2	% of error
107	3672.5	3679.4	0.187882914	3275.4	3308	0.995298284
200	787.6	792	0.558659218	1905	1840	3.412073491
307	492.5	490.2	0.467005076	598.3	602	0.618418853
400	448.4	450.2	0.401427297	476	488	2.521008403
507	256.82	255	0.708667549	372.5	383.2	2.872483221
600	482.7	440.5	8.74249016	886.7	869.2	1.973610015
707	376.2	382.5	1.674641148	0	0	-
800	320	307	4.0625	287	278	3.135888502
907	778	773	0.642673522	398.6	386	3.161063723
1000	649.2	650.4	0.184842884	287.3	288.5	0.417681866
2000	87.2	82.3	5.619266055	189.2	201	6.236786469
3000	43	45	4.651162791	105.2	100.4	4.562737643

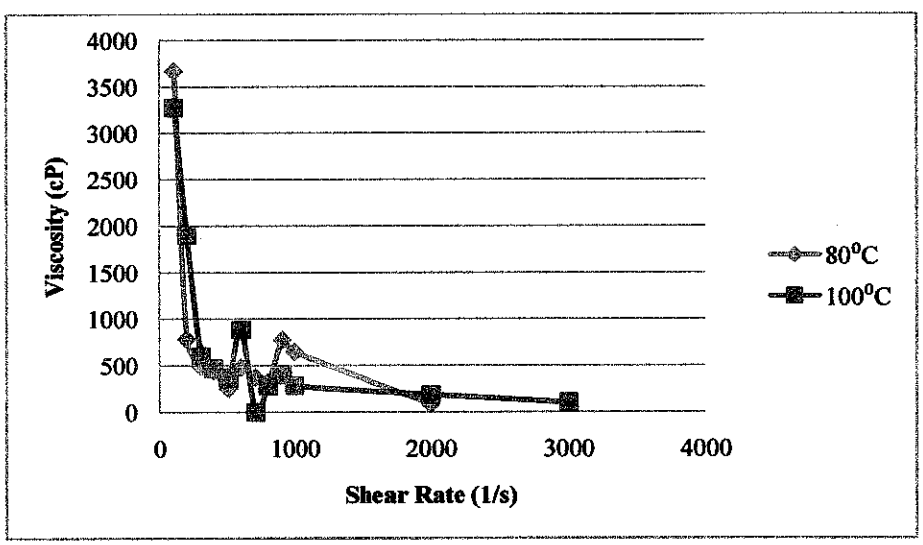

Figure 12: Viscosity trend of 20 ppm solution at 80°C and 100°C using Method 1

Table 5: Results for 50 ppm solution using method 1

50 ppm dilute solution						
Shear Rate (1/s)	Viscosity (cP)					
	80°C			100°C		
	1	2	% of error	1	2	% of error
107	5743.5	5729.2	0.248977105	5382	5345	0.687476774
200	4872.8	4776	1.986537514	4234.5	4237	0.059038848
307	2859.4	2756.9	3.584668112	2653.6	2651	0.097980103
400	1475.2	1654	12.12039046	1213.7	1235	1.754964159
507	952	987.5	3.728991597	872.4	867.7	0.538743696
600	782.4	778.4	0.511247444	704.5	717.2	1.802696948
707	695	713	2.589928058	0	0	-
800	502	512.2	2.03187251	745.3	752.3	0.939219106
907	449.5	450	0.111234705	659.7	660	0.045475216
1000	285.4	287.3	0.665732306	209	218.5	4.545454545
2000	100.5	98.5	1.990049751	87	89	2.298850575
3000	67	79	17.91044776	46.8	47.2	0.854700855

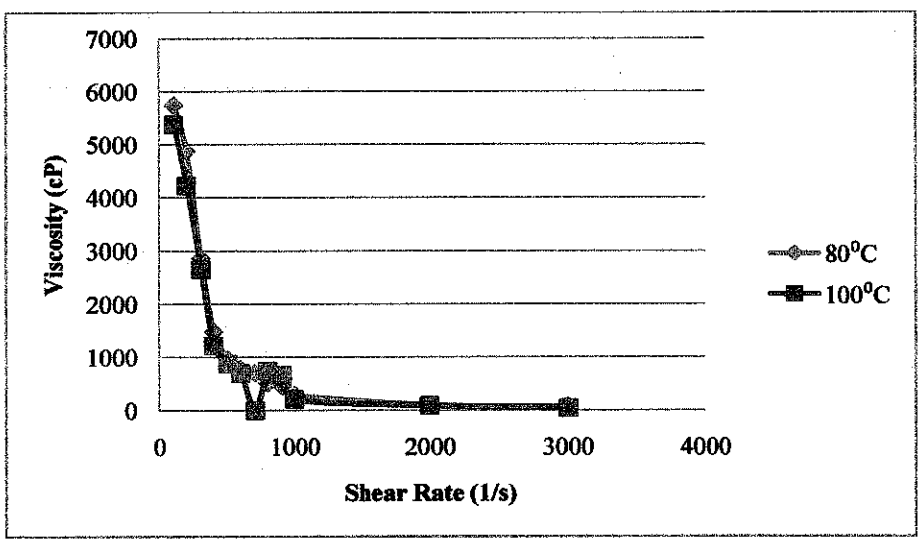

Figure 13: Viscosity trend of 50 ppm solution at 80°C and 100°C using Method 1

Table 6: Results for 10 ppm solution using method 2

10 ppm dilute solution						
Shear Rate (1/s)	Viscosity (cP)					
	80°C			100°C		
	1	2	% of error	1	2	% of error
20	437.57	441.2	0.829581553	411.26	400.28	2.669843894
30	426.37	416.4	2.33834463	398.63	389.23	2.358076412
40	410	408.48	0.370731707	387	379.57	1.919896641
50	386.25	392.49	1.615533981	368.33	357	3.076045937
60	378.4	384.39	1.582980973	354.69	350.3	1.237700527
70	368.3	372.36	1.102362205	347	343.58	0.985590778
80	363.8	368.29	1.234194612	338.52	330.2	2.457757296
90	356.83	352.47	1.221870358	329.4	312	5.282331512
107	347.7	338.41	2.671843543	315.63	304.48	3.532617305
200	329	321.3	2.340425532	296.54	284.5	4.060160518
307	307.94	300.18	2.519971423	279.14	266.17	4.646413986
400	274.3	270.28	1.465548669	251.3	239.64	4.639872662
507	248.69	256.42	3.108287426	233.1	226.49	2.835692836
600	231	226.4	1.991341991	215.75	200.58	7.031286211
707	218.59	213.72	2.227915275	197.4	184.39	6.590678825
800	195	191.57	1.758974359	173.57	167.3	3.61237541
907	178.43	170.17	4.629266379	152.4	155.29	1.896325459
1000	157.21	161.28	2.588893836	139.29	141.32	1.457391055
1500	118.5	95.48	19.42616034	98.17	92.19	6.091473974
2000	84.3	82.23	2.455516014	71.27	73.19	2.693980637
2500	68.11	70.18	3.039201292	58.16	60.63	4.246905089
3000	60.12	58.37	2.910844977	49.18	51.29	4.290361936

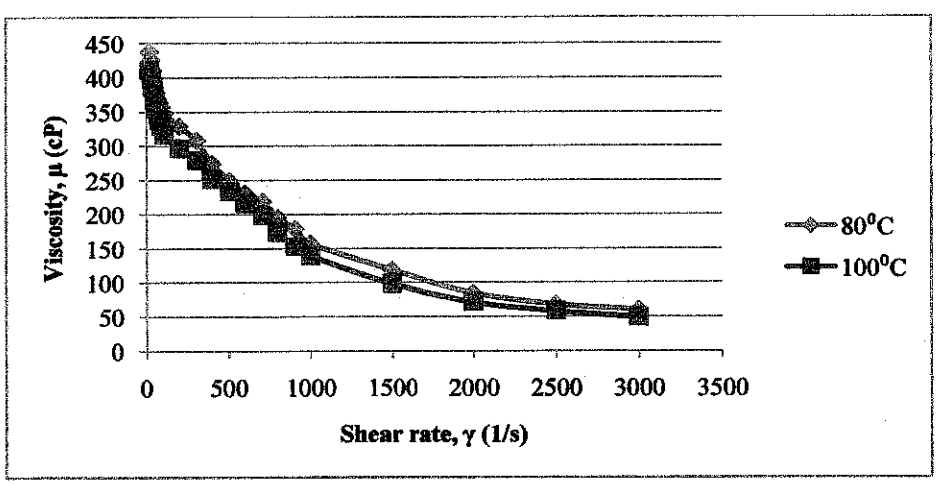

Figure 14: Viscosity trend of 10 ppm solution at 80^0C and 100^0C using Method 2

Table 7: Results for 20 ppm solution using method 2

20 ppm dilute solution						
Shear Rate (1/s)	Viscosity (cP)					
	80°C			100°C		
	1	2	% of error	1	2	% of error
20	548.35	553.28	0.899060819	522.48	521.47	0.193308835
30	534.75	539.31	0.852734923	514.2	500.24	2.714896927
40	521.84	511.53	1.975701364	495.25	487.39	1.587077234
50	507	500.48	1.285996055	481.97	477	1.031184514
60	494.59	489.3	1.069572777	467.38	465.28	0.449313193
70	487.13	478.38	1.796235091	455.31	448.36	1.52643254
80	475.38	476.42	0.218772351	441	435.35	1.281179138
90	463.17	459.85	0.716799447	427.96	432.2	0.990746799
107	450.28	442	1.838855823	412.48	404.31	1.980702095
200	437	423.73	3.036613272	399.89	387.47	3.10585411
307	413.74	394.29	4.701019964	382	379.12	0.753926702
400	395.84	384.3	2.915319321	360.96	355.48	1.518173759
507	377.54	366.48	2.929490915	342.58	338	1.336914005
600	359.63	362.3	0.742429719	319.93	308.4	3.603913356
707	346.65	338.59	2.325111784	301.28	297.15	1.370817844
800	324.47	312	3.843190434	284.27	292.58	2.923277166
907	307	297.4	3.127035831	263.71	254.38	3.537977324
1000	286.69	276.38	3.596218912	237.5	223.3	5.978947368
1500	249.78	253.49	1.48530707	215.84	207.2	4.002965159
2000	214	201.4	5.887850467	193.29	189.47	1.976305034
2500	189.74	178.3	6.029303257	167.75	154	8.196721311
3000	162.58	159	2.201992865	143.53	127	11.51675608

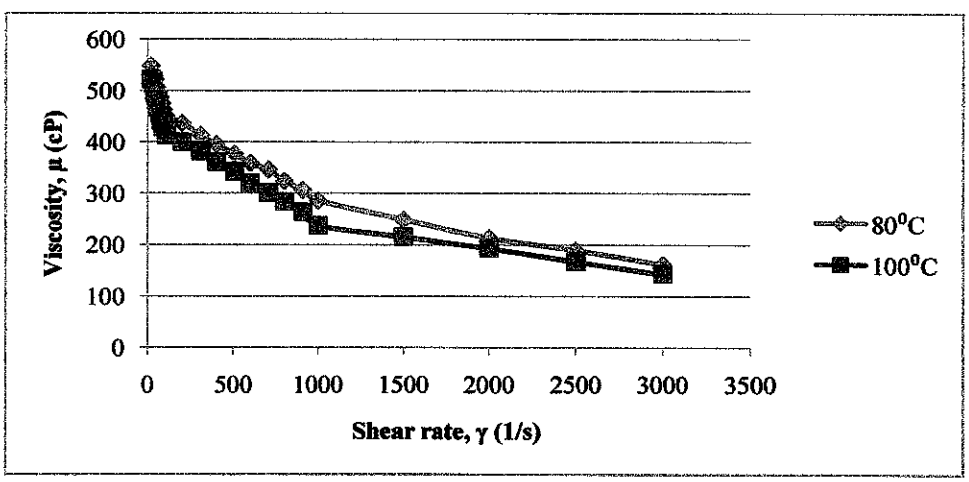

Figure 15: Viscosity trend of 20 ppm solution at 80°C and 100°C using Method 2

Table 8: Results for 50 ppm solution using method 2

50 ppm dilute solution						
Shear Rate (1/s)	Viscosity (cP)					
	80°C			100°C		
	1	2	% of error	1	2	% of error
20	783.28	794.65	1.451588193	758.37	763.28	0.647441223
30	767.84	773	0.672015003	743.29	739.27	0.540838704
40	758.39	752.34	0.797742586	730.16	730.39	0.031499945
50	743.86	739.49	0.587476138	716.38	722.3	0.826377062
60	736.49	728.47	1.088948933	705.47	713	1.067373524
70	723.48	714	1.310333389	693	703.23	1.476190476
80	710.2	704.37	0.820895522	685.46	689.74	0.624398214
90	702.69	694.24	1.202521738	673.92	680.37	0.957086895
107	685.53	677.38	1.188861173	658.39	662.35	0.601467215
200	663.83	669.32	0.827018966	636.36	627.19	1.441008234
307	646.48	639.24	1.119910902	613.98	600.24	2.237857911
400	621	612.3	1.400966184	589.37	577	2.098851316
507	597.48	584	2.256142465	572.38	562.32	1.75757364
600	582.39	563.48	3.246965092	553	549.3	0.669077758
707	556.74	558.39	0.296368143	529.63	512.37	3.25887884
800	528.48	517.27	2.121177717	501.29	498.93	0.470785374
907	501.27	493.2	1.609910827	476.35	465.48	2.281935552
1000	478.28	482.37	0.855147612	452.37	461.28	1.969626633
1500	453.26	442.75	2.318757446	417.31	400.34	4.066521291
2000	417.83	395.42	5.363425317	378.49	368	2.771539539
2500	397	382	3.778337531	344.57	332.43	3.523231854
3000	361.67	359.4	0.627643985	312	305.68	2.025641026

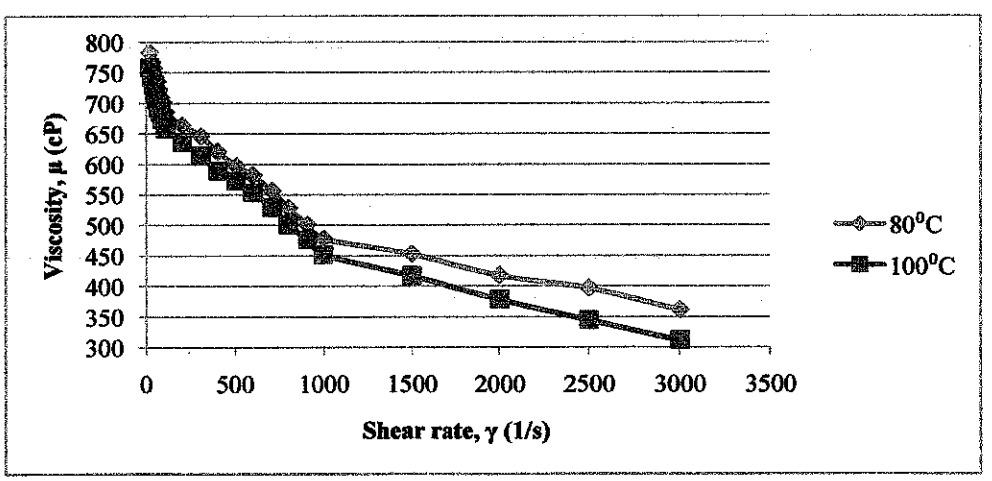

Figure 16: Viscosity trend of 50 ppm solution at 80°C and 100°C using Method 2

Table 9: Results for 700 ppm solution using method 2

700 ppm dilute solution						
Shear Rate (1/s)	Viscosity (cP)					
	80°C			100°C		
	1	2	% of error	1	2	% of error
20	2574.3	2583.2	0.345725051	2529.5	2517.3	0.482308757
30	2556.2	2542.3	0.543775917	2501.3	2495.2	0.243873186
40	2538.7	2537.4	0.051207311	2476.2	2469.9	0.254422098
50	2524.4	2518.3	0.241641578	2458.3	2438.4	0.809502502
60	2502.8	2496.5	0.251718076	2432.4	2425.3	0.291892781
70	2487.2	2476.9	0.414120296	2409	2391.7	0.718140307
80	2471.9	2466	0.238682795	2384	2383.4	0.025167785
90	2459.5	2449.7	0.398454971	2369.6	2357.2	0.523295071
107	2438	2421.3	0.684987695	2348.2	2352.9	0.200153309
200	2411.2	2395.1	0.667717319	2316.3	2304	0.531019298
307	2379.4	2383.4	0.168109607	2287.2	2274.3	0.564008395
400	2353	2348.7	0.182745431	2253.8	2238	0.701038247
507	2328.9	2303.2	1.103525269	2229	2213.2	0.708838044
600	2294.7	2287.5	0.313766505	2194.3	2187.8	0.29622203
707	2264.3	2278.4	0.622709005	2168.4	2153.5	0.687142594
800	2241.8	2231.9	0.441609421	2139.8	2104.3	1.659033555
907	2218	2203.5	0.65374211	2092.6	2083.2	0.44920195
1000	2184.4	2168.3	0.737044497	2074.3	2074.1	0.009641807
1500	2137	2142.3	0.248011231	2017.9	2001.3	0.822637395
2000	2089.5	2074	0.741804259	1973.2	1967.4	0.29393878
2500	2048.3	2049.3	0.048820973	1928.6	1902.5	1.353313284
3000	1997.2	2004.3	0.355497697	1873	1793	4.271222637

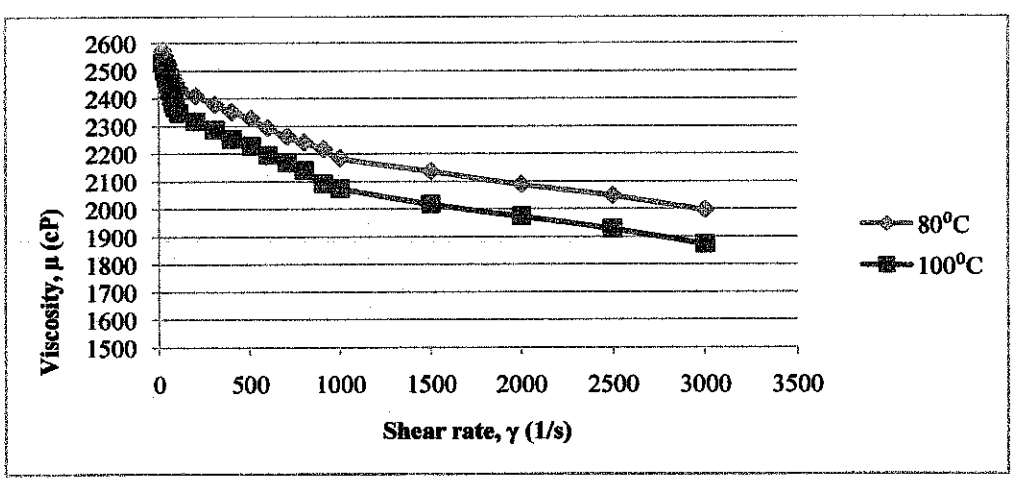

Figure 17: Viscosity trend of 700 ppm solution at 80°C and 100°C using Method 2

Table 3, 4 and 5 are the results obtained from the rheological study conducted using the first method. On the other hand, Figure 11, 12 and 13 are the corresponding plots of viscosity trend for data in Table 3, 4 and 5. From those data table we can clearly see that at certain shear rate, the value of viscosity gained is equal to zero. This is due to the reason that, the sample placed on the viscometer might be way too dilute or way too concentrated. This causes the viscosity of that particular sample to be out of spindle 6 measurable range.

From the plots in Figure 11, 12 and 13 we can clearly see that it is not a smooth plot that we expect to get from the viscosity study. Once it reaches a certain range of shear rates, in this case 400 (1/s) to 1000 (1/s), the viscosity value tend to fluctuate. This shows that using a new sample from a same sample bottle for every single shear rate is not the ideal way of conducting this experiment.

Although we a using the sample from the same sample bottle, it does not assure us that the concentration of polymer spread throughout the bottle will be the same. Due to certain parameters it might result in uneven spread of polymer concentration in the sample bottle. For an example, the gravity force. Once we have diluted the master solution into dilute concentration of 10 ppm to 50 ppm, we will pour it into the sample bottle and store it for a day to allow hydration to occur. During this particular period of time, the gravity force plays a role in pulling the polymer down to the bottom of the sample bottle and while conducting the experiment we tend to take the sample from different location in the sample bottle thus resulting in the fluctuation of viscosity values.

Another parameter which plays an important role in the fluctuation of viscosity value is the gel strength of the long chain polymer. Due to the hydration period of a day, there is a high possibility for the polymer in the sample bottle to gel up and form a long chain link with high strength. This particular phenomena has the ability to suspend the gravitational force and hold its position at any point of location in the sample bottle, resulting in the polymer to be concentrated at a certain point rather

than throughout the sample bottle. That is the reason why I used the second method to rerun the experiment.

Table 6 to table 9 shows the results of the rheological study conducted using the second method. Whereas, figure 14 to figure 17 are the corresponding plots of viscosity trend for data in table 6 to table 9. The second method proves to be a better way of conducting the experiment due to the reason that, there are no values spotted to be out of the measurable range by spindle 6. In this particular method we used the same sample throughout the experiment for a specific temperature.

When we have a look at the viscosity trend of HPAM for the second method of experiment, it shows a smooth curve rather than a fluctuating curve shown by plots for the first method. With the increase of shear rate, it shows that the viscosity of HPAM is reducing. This proves that, at this particular range of shear rates, both master solution and dilute solutions are exhibiting shear thinning fluid characteristic. Thus, it proves the statement that HPAM is a Pseudoplatic polymer solution for this particular range of shear rates. This is due to the reason that the long chain polymer is being stretched by the rotational speed of the cone. The strength to resist the stretch is being weakened by the rotating cone which pulls the polymer apart.

The viscosity of the solution decreases as the temperature increases; it is proven when we compare the value of viscosity between solutions with same concentration but different temperatures. The reduction in viscosity may be caused by the stretched polymer chain as the temperature rises. As temperature increases, the polymer chain will tend to break its stronghold, resulting in less viscous solution.

On the other hand, temperature seems to have a minimal effect on the viscosity of the polymer, as both elevated temperatures show similar reduction trend. This is due to the strength of the long-chain polymer backbone that resist the polymer stretching to occur at a given shear rate.

Furthermore, the viscosity trend in figure 14 to figure 17 shows that the viscosity of HPAM does not reduces smoothly but it tend to deviate at certain shear rate. It shows three different straight lines for three different range of shear rates which are, 20 1/s to 107 1/s, 107 1/s to 1000 1/s and 1000 1/s to 3000 1/s. Normally, viscosity trend tend to be a smooth logarithmic line decreasing with increasing shear rate but it is quite different in this case.

This is due to the impact of both temperature and shear rate. If we see closely, from 20 1/s to 107 1/s the increment of shear rate is more or less 10 1/s but from 107 1/s to 200 1/s, there is a sudden increase of roughly 100 1/s. The sudden change in the inertia of the sample and the torque of the rotating cone results in sudden reduction of viscosity. Plus, with the help of elevated temperature, the polymer solution is being stretched greatly once there is a sudden change in shear rate increment.

When we compare the viscosity of solutions with different concentrations, it shows an increment in viscosity as the concentration of the solution increases. Higher concentration of solution means more solute is in the solution to make the solution thick. Plus, when we talk about polymer solution it can be stated higher concentration of polymer solution has a longer chain of polymer or it might have cross linked chain due to the hydration period and agitation. The strength of the long-chain polymer tends to be higher in solution with higher concentration due to the more number of solute present in that particular solution. When there is more solute present in a solution the bond tends to be stronger as the polymer will be linked up closely to each other.

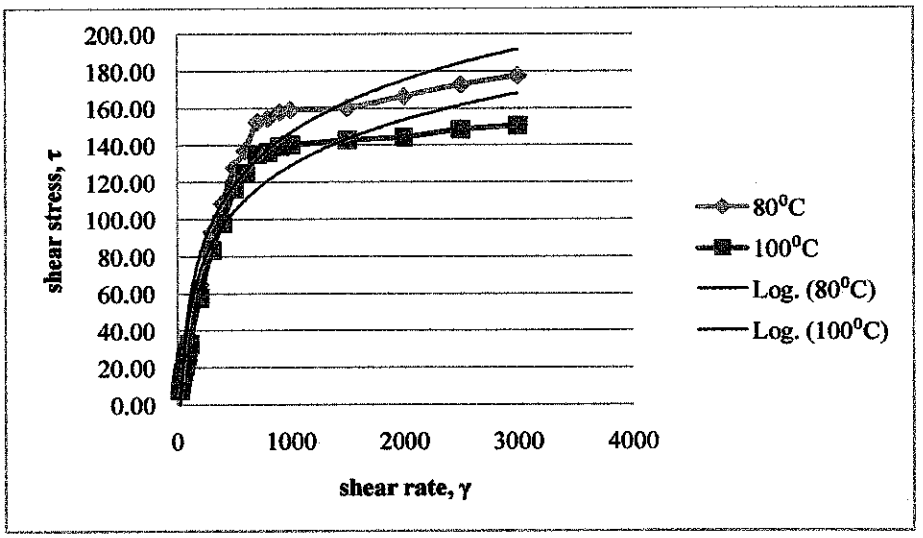

Figure 18: Shear stress vs shear rate plot of 10 ppm solution

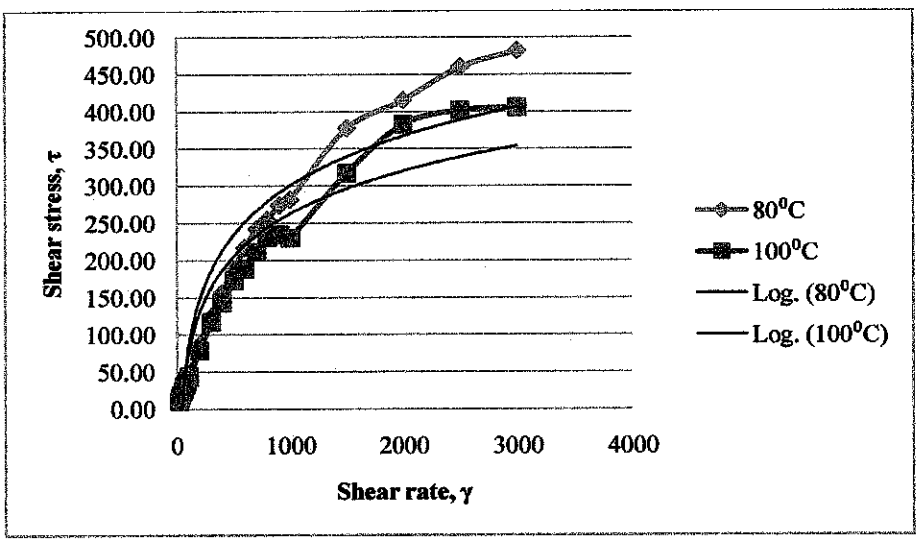

Figure 19: Shear stress vs shear rate plot of 20 ppm solution

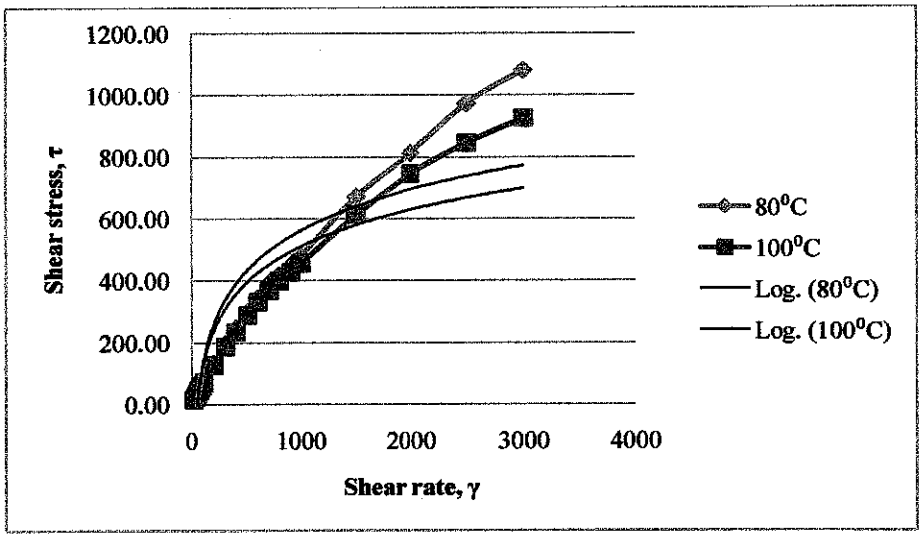

Figure 20: Shear stress vs shear rate plot of 50 ppm solution

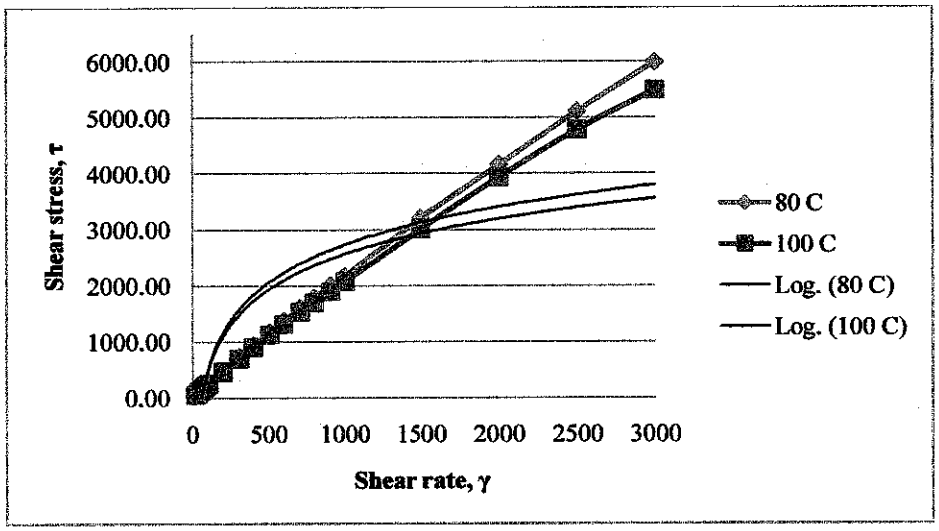

Figure 21: Shear stress vs shear rate plot of 700 ppm solution

Figure 18 to figure 21 shows the plot of shear stress against shear rate for four different concentration solutions. This plot is used to determine the best viscosity model in order to measure the flow behavior index (n) value and the consistency index (k) value. From all those four plots, it is proven that the best viscosity model is the Power Law model which is also known as the Ostwald-de Waele model.

The following equation is used to determine the both *k* and *n* values:

$$\mu = k\gamma^{(n-1)}$$

Where, μ = viscosity (Pa.s)

k = consistency index ($Pa.s^n$)

n = flow behavior index

γ = shear rate (1/s)

In order to find the *k* and *n* values, we need to introduce log to both side of the equation which will result in the following equation:

$$\log \mu = \log k + (n-1) \log \gamma$$

Where log μ is the y-axis of the plot, log γ is the x-axis of the plot, log k is the intercept point at y-axis and (n-1) is the slope of the plot. The following table shows the calculated value of *k* and *n* by plotting the log μ against log γ curve.

Table 10: The flow behavior index (n) and the consistency index (k) values for various ranges of shear rates.

Polymer Concentration	Temperature	Range of shear rate (1/s)	n	k (Pa.s)
HPAM 10ppm	80°C	20 - 107	0.8513	0.6965
		107 - 1000	0.656	1.9706
		1000 - 3000	0.1034	76.754
	100°C	20 - 107	0.8349	0.6861
		107 - 1000	0.6465	1.8685
		1000 - 3000	0.065	89.04
HPAM 20ppm	80°C	20 - 107	0.8754	0.814
		107 - 1000	0.8028	1.2089
		1000 - 3000	0.4838	10.37
	100°C	20 - 107	0.8561	0.8251
		107 - 1000	0.7633	1.374
		1000 - 3000	0.5304	6.269
HPAM 50ppm	80°C	20 - 107	0.9138	1.0323
		107 - 1000	0.8431	1.515
		1000 - 3000	0.7413	2.9094
	100°C	20 - 107	0.9187	0.9802
		107 - 1000	0.8379	1.4887
		1000 - 3000	0.6486	5.2674
HPAM 700ppm	80°C	20 - 107	0.9652	2.8747
		107 - 1000	0.9516	3.101
		1000 - 3000	0.924	3.702
	100°C	20 - 107	0.9551	2.906
		107 - 1000	0.9432	3.1203
		1000 - 3000	0.8951	4.3152

From the table above, we can clearly see that all the flow behavior (n) index values are below 1, which brings to a conclusion that HPAM still behaves as a non-Newtonian fluid although the temperature has been elevated. If we compare the *n* value of 10 ppm solution with 20 ppm solution at 80^0C, we can see the increment of value due to the increase in concentration of the solution.

Furthermore, highly concentrated solution tend to have higher value of *n* which shows that there is a possibility for the *n* value to cross the shear thinning region (a

fluid is categorized as shear thinning fluid if the $n < 1$, when $n > 1$, the fluid shows shear thickening behavior)

On the other hand, results in table 10 shows that with increasing value of shear rate, the n value tend to decrease. This is due to the effect of rotational speed on the polymer solution which stretches the long-chain polymer to make it easier to flow.

CHAPTER 5: CONCLUSION & RECOMMENDATION

5.1 Conclusion

In this project there are six parameters which will be tested in the experimental work namely, pressure, temperature, master concentration, dilute concentration, shear rate and hydration period. It is decided that three of the parameters which are hydration period, pressure and master concentration will remain constant throughout the experiment. Whereas, the other three parameters will be varied to understand the viscosity behavior of HPAM under elevated temperature and normal pressure condition.

From the experiment which has been carried, it can be concluded that the main objective of this study which is to investigate the effect of temperature and shear rate on the HPAM solution has been achieved. From the data gained it is proven that temperature gives minimal effect on the viscosity trend of HPAM solution, this is due to the reason that the viscosity trend for both 80^0C and 100^0C seems to be decreasing in the same manner. On the other hand, the comparison between both temperatures for a certain concentration of solution for an example 50 ppm solution shows that, 100^0C gives a lesser viscosity value than 80^0C.

The viscosity trend also proves that increment in shear rate results in decrease in viscosity value. Increasing the shear rate makes the polymer solution to be stretched. This particular point proves that the HPAM solution still exhibits Non-Newtonian fluid properties under elevated temperature condition.

Furthermore, the calculation of flow behavior index (n) value shows that partially hydrolyzed polyacrylamide is a shear thinning polymer solution within the tested range of shear rate. This is due to the reason that the n value is below 1 which shows that it is still in the shear thinning region. This study also proves the statement made

by Lewandowska in his research, where there is a possibility for HPAM to show the shear thickening effect because at very low value of concentration and high value of shear rate, the n value seems to be closer to 1.

5.2 Recommendations

This study can be extended by taking into account the effect of different hydration period and also different master concentrations. If this study can prove that HPAM can sustain its properties and characteristics under the selected elevated temperature range, we can move a step further by taking into account high pressure and high temperature conditions.

Further research can be carried out by investigating the effect of shear rates below 20 1/s, this will help to determine the yield point of the shear stress and also will help us to investigate the viscosity trend below 20 1/s. Shear rates above 3000 1/s can also be considered which will help us to determine whether HPAM shows shear thickening effect or not at very high shear rates. The early sign from this particular study shows that there is a possibility for HPAM to show shear thickening characteristics.

Plus, a proper study using complete water based mud system with the inclusion of HPAM as its additive can be tested under the chosen high pressure and high temperature range. This particular study will be very beneficial to the drilling fluids companies out there. It will certainly enable them to operate with water based mud system under extreme condition which is far cheaper and environmental friendly.

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APPENDICES

Data tables using Method 1 of rheology testing

10 ppm dilute solution								
Shear Rate (1/s)	Viscosity (cP)							
	80°C				100°C			
	1	2	% of error	average	1	2	% of error	average
107	4921.8	4931	0.186923483	4926.40	4587.2	4612	0.54063481	4599.6
200	0	0	-	0.00	782.4	804	2.760736196	793.2
307	4	7	75	5.50	0	0	-	0
400	44.1	53.2	20.63492063	48.65	78.3	82.3	5.108556833	80.3
507	0	0	-	0.00	425.7	423.5	0.516795866	424.6
600	542.6	539.6	0.552893476	541.10	257.4	248	3.651903652	252.7
707	78	85	8.974358974	81.50	459.9	460	0.021743857	459.95
800	324.5	320	1.386748844	322.25	338.2	344	1.714961561	341.1
907	243	248.3	2.181069959	245.65	287.3	278.54	3.049077619	282.92
1000	87	90	3.448275862	88.50	0	0	-	0
2000	0	0	-	0.00	887.5	880.2	0.822535211	883.85
3000	54	55	1.851851852	54.50	89.4	90	0.67114094	89.7

20 ppm dilute solution								
Shear Rate (1/s)	Viscosity (cP)							
	80°C				100°C			
	1	2	% of error	average	1	2	% of error	average
107	3672.5	3679.4	0.187882914	3675.95	3275.4	3308	0.995298284	3291.7
200	787.6	792	0.558659218	789.80	1905	1840	3.412073491	1872.5
307	492.5	490.2	0.467005076	491.35	598.3	602	0.618418853	600.15
400	448.4	450.2	0.401427297	449.30	476	488	2.521008403	482
507	256.82	255	0.708667549	255.91	372.5	383.2	2.872483221	377.85
600	482.7	440.5	8.74249016	461.60	886.7	869.2	1.973610015	877.95
707	376.2	382.5	1.674641148	379.35	0	0	-	0
800	320	307	4.0625	313.50	287	278	3.135888502	282.5
907	778	773	0.642673522	775.50	398.6	386	3.161063723	392.3
1000	649.2	650.4	0.184842884	649.80	287.3	288.5	0.417681866	287.9
2000	87.2	82.3	5.619266055	84.75	189.2	201	6.236786469	195.1
3000	43	45	4.651162791	44.00	105.2	100.4	4.562737643	102.8

30 ppm dilute solution								
Shear Rate (1/s)	Viscosity (cP)							
	80°C				100°C			
	1	2	% of error	average	1	2	% of error	average
107	4875.4	4902	0.545596259	4888.70	4285.5	4312	0.618364252	4298.75
200	2385	2386	0.041928721	2385.50	1965	1899	3.358778626	1932
307	1858	1845	0.699677072	1851.50	982.5	978.3	0.427480916	980.4
400	859.2	860.5	0.151303538	859.85	764.8	765	0.026150628	764.9
507	674.5	660.5	2.075611564	667.50	572.9	568.2	0.820387502	570.55
600	498.4	500.6	0.44141252	499.50	0	0	-	0
707	842.6	840	0.308568716	841.30	765.2	746.5	2.443805541	755.85
800	0	0	-	0.00	592.3	600.3	1.350666892	596.3
907	504	500.2	0.753968254	502.10	0	0	-	0
1000	209.5	210.5	0.477326969	210.00	165	147.8	10.42424242	156.4
2000	184.5	176	4.60704607	180.25	90	89	1.111111111	89.5
3000	56	50	10.71428571	53.00	74.2	75.2	1.347708895	74.7

40 ppm dilute solution								
Shear Rate (1/s)	Viscosity (cP)							
	80°C				100°C			
	1	2	% of error	average	1	2	% of error	average
107	5264.6	5275.2	0.201344832	5269.90	4982.4	4943	0.790783558	4962.7
200	3827	3875	1.254246146	3851.00	3398	3389	0.264861683	3393.5
307	1759.4	1762	0.147777651	1760.70	1683	1712.5	1.752822341	1697.75
400	854.7	887.5	3.837603838	871.10	715.8	723.4	1.061749092	719.6
507	694.1	700.2	0.878835903	697.15	582	602.4	3.505154639	592.2
600	551.4	548.4	0.544069641	549.90	448.9	450.6	0.378703497	449.75
707	0	0	-	0.00	852.8	843	1.149155722	847.9
800	782.4	767.5	1.904396728	774.95	0	0	-	0
907	401.2	387.2	3.489531406	394.20	421.7	432.5	2.561062367	427.1
1000	382.4	367.5	3.896443515	374.95	189	178	5.82010582	183.5
2000	189	178	5.82010582	183.50	109.5	90.5	17.35159817	100
3000	75	65	13.33333333	70.00	87	78.5	9.770114943	82.75

50 ppm dilute solution								
Shear Rate (1/s)	Viscosity (cP)							
	80°C				100°C			
	1	2	% of error	average	1	2	% of error	average
107	5743.5	5729.2	0.248977105	5736.35	5382	5345	0.687476774	5363.5
200	4872.8	4776	1.986537514	4824.40	4234.5	4237	0.059038848	4235.75
307	2859.4	2756.9	3.584668112	2808.15	2653.6	2651	0.097980103	2652.3
400	1475.2	1654	12.12039046	1564.60	1213.7	1235	1.754964159	1224.35
507	952	987.5	3.728991597	969.75	872.4	867.7	0.538743696	870.05
600	782.4	778.4	0.511247444	780.40	704.5	717.2	1.802696948	710.85
707	695	713	2.589928058	704.00	0	0	-	0
800	502	512.2	2.03187251	507.10	745.3	752.3	0.939219106	748.8
907	449.5	450	0.111234705	449.75	659.7	660	0.045475216	659.85
1000	285.4	287.3	0.665732306	286.35	209	218.5	4.545454545	213.75
2000	100.5	98.5	1.990049751	99.50	87	89	2.298850575	88
3000	67	79	17.91044776	73.00	46.8	47.2	0.854700855	47

Data tables using Method 2 of rheology testing

10 ppm dilute solution								
Shear Rate (1/s)	Viscosity (cP)							
	80°C				100°C			
	1	2	% of error	average	1	2	% of error	average
20	437.57	441.2	0.829581553	439.39	411.26	400.28	2.669843894	405.77
30	426.37	416.4	2.33834463	421.39	398.63	389.23	2.358076412	393.93
40	410	408.48	0.370731707	409.24	387	379.57	1.919896641	383.285
50	386.25	392.49	1.615533981	389.37	368.33	357	3.076045937	362.665
60	378.4	384.39	1.582980973	381.40	354.69	350.3	1.237700527	352.495
70	368.3	372.36	1.102362205	370.33	347	343.58	0.985590778	345.29
80	363.8	368.29	1.234194612	366.05	338.52	330.2	2.457757296	334.36
90	356.83	352.47	1.221870358	354.65	329.4	312	5.282331512	320.7
107	347.7	338.41	2.671843543	343.06	315.63	304.48	3.532617305	310.055
200	329	321.3	2.340425532	325.15	296.54	284.5	4.060160518	290.52
307	307.94	300.18	2.519971423	304.06	279.14	266.17	4.646413986	272.655
400	274.3	270.28	1.465548669	272.29	251.3	239.64	4.639872662	245.47
507	248.69	256.42	3.108287426	252.56	233.1	226.49	2.835692836	229.795
600	231	226.4	1.991341991	228.70	215.75	200.58	7.031286211	208.165
707	218.59	213.72	2.227915275	216.16	197.4	184.39	6.590678825	190.895
800	195	191.57	1.758974359	193.29	173.57	167.3	3.61237541	170.435
907	178.43	170.17	4.629266379	174.30	152.4	155.29	1.896325459	153.845
1000	157.21	161.28	2.588893836	159.25	139.29	141.32	1.457391055	140.305
1500	118.5	95.48	19.42616034	106.99	98.17	92.19	6.091473974	95.18
2000	84.3	82.23	2.455516014	83.27	71.27	73.19	2.693980637	72.23
2500	68.11	70.18	3.039201292	69.15	58.16	60.63	4.246905089	59.395
3000	60.12	58.37	2.910844977	59.25	49.18	51.29	4.290361936	50.235

20 ppm dilute solution								
Shear Rate (1/s)	Viscosity (cP)							
	80°C				100°C			
	1	2	% of error	average	1	2	% of error	average
20	548.35	553.28	0.899060819	550.82	522.48	521.47	0.193308835	521.98
30	534.75	539.31	0.852734923	537.03	514.2	500.24	2.714896927	507.22
40	521.84	511.53	1.975701364	516.69	495.25	487.39	1.587077234	491.32
50	507	500.48	1.285996055	503.74	481.97	477	1.031184514	479.49
60	494.59	489.3	1.069572777	491.95	467.38	465.28	0.449313193	466.33
70	487.13	478.38	1.796235091	482.76	455.31	448.36	1.52643254	451.84
80	475.38	476.42	0.218772351	475.90	441	435.35	1.281179138	438.18
90	463.17	459.85	0.716799447	461.51	427.96	432.2	0.990746799	430.08
107	450.28	442	1.838855823	446.14	412.48	404.31	1.980702095	408.40
200	437	423.73	3.036613272	430.37	399.89	387.47	3.10585411	393.68
307	413.74	394.29	4.701019964	404.02	382	379.12	0.753926702	380.56
400	395.84	384.3	2.915319321	390.07	360.96	355.48	1.518173759	358.22
507	377.54	366.48	2.929490915	372.01	342.58	338	1.336914005	340.29
600	359.63	362.3	0.742429719	360.97	319.93	308.4	3.603913356	314.17
707	346.65	338.59	2.325111784	342.62	301.28	297.15	1.370817844	299.22
800	324.47	312	3.843190434	318.24	284.27	292.58	2.923277166	288.43
907	307	297.4	3.127035831	302.20	263.71	254.38	3.537977324	259.05
1000	286.69	276.38	3.596218912	281.54	237.5	223.3	5.978947368	230.40
1500	249.78	253.49	1.48530707	251.64	215.84	207.2	4.002965159	211.52
2000	214	201.4	5.887850467	207.70	193.29	189.47	1.976305034	191.38
2500	189.74	178.3	6.029303257	184.02	167.75	154	8.196721311	160.88
3000	162.58	159	2.201992865	160.79	143.53	127	11.51675608	135.27

50 ppm dilute solution								
Shear Rate (1/s)	Viscosity (cP)							
	80°C				100°C			
	1	2	% of error	average	1	2	% of error	average
20	783.28	794.65	1.451588193	788.97	758.37	763.28	0.647441223	760.83
30	767.84	773	0.672015003	770.42	743.29	739.27	0.540838704	741.28
40	758.39	752.34	0.797742586	755.37	730.16	730.39	0.031499945	730.28
50	743.86	739.49	0.587476138	741.68	716.38	722.3	0.826377062	719.34
60	736.49	728.47	1.088948933	732.48	705.47	713	1.067373524	709.24
70	723.48	714	1.310333389	718.74	693	703.23	1.476190476	698.12
80	710.2	704.37	0.820895522	707.29	685.46	689.74	0.624398214	687.60
90	702.69	694.24	1.202521738	698.47	673.92	680.37	0.957086895	677.15
107	685.53	677.38	1.188861173	681.46	658.39	662.35	0.601467215	660.37
200	663.83	669.32	0.827018966	666.58	636.36	627.19	1.441008234	631.78
307	646.48	639.24	1.119910902	642.86	613.98	600.24	2.237857911	607.11
400	621	612.3	1.400966184	616.65	589.37	577	2.098851316	583.19
507	597.48	584	2.256142465	590.74	572.38	562.32	1.75757364	567.35
600	582.39	563.48	3.246965092	572.94	553	549.3	0.669077758	551.15
707	556.74	558.39	0.296368143	557.57	529.63	512.37	3.25887884	521.00
800	528.48	517.27	2.121177717	522.88	501.29	498.93	0.470785374	500.11
907	501.27	493.2	1.609910827	497.24	476.35	465.48	2.281935552	470.92
1000	478.28	482.37	0.855147612	480.33	452.37	461.28	1.969626633	456.83
1500	453.26	442.75	2.318757446	448.01	417.31	400.34	4.066521291	408.83
2000	417.83	395.42	5.363425317	406.63	378.49	368	2.771539539	373.25
2500	397	382	3.778337531	389.50	344.57	332.43	3.523231854	338.50
3000	361.67	359.4	0.627643985	360.54	312	305.68	2.025641026	308.84

700 ppm dilute solution								
Shear Rate (1/s)	Viscosity (cP)							
	80°C				100°C			
	1	2	% of error	average	1	2	% of error	average
20	2574.3	2583.2	0.345725051	2578.75	2529.5	2517.3	0.482308757	2523.40
30	2556.2	2542.3	0.543775917	2549.25	2501.3	2495.2	0.243873186	2498.25
40	2538.7	2537.4	0.051207311	2538.05	2476.2	2469.9	0.254422098	2473.05
50	2524.4	2518.3	0.241641578	2521.35	2458.3	2438.4	0.809502502	2448.35
60	2502.8	2496.5	0.251718076	2499.65	2432.4	2425.3	0.291892781	2428.85
70	2487.2	2476.9	0.414120296	2482.05	2409	2391.7	0.718140307	2400.35
80	2471.9	2466	0.238682795	2468.95	2384	2383.4	0.025167785	2383.70
90	2459.5	2449.7	0.398454971	2454.60	2369.6	2357.2	0.523295071	2363.40
107	2438	2421.3	0.684987695	2429.65	2348.2	2352.9	0.200153309	2350.55
200	2411.2	2395.1	0.667717319	2403.15	2316.3	2304	0.531019298	2310.15
307	2379.4	2383.4	0.168109607	2381.40	2287.2	2274.3	0.564008395	2280.75
400	2353	2348.7	0.182745431	2350.85	2253.8	2238	0.701038247	2245.90
507	2328.9	2303.2	1.103525269	2316.05	2229	2213.2	0.708838044	2221.10
600	2294.7	2287.5	0.313766505	2291.10	2194.3	2187.8	0.29622203	2191.05
707	2264.3	2278.4	0.622709005	2271.35	2168.4	2153.5	0.687142594	2160.95
800	2241.8	2231.9	0.441609421	2236.85	2139.8	2104.3	1.659033555	2122.05
907	2218	2203.5	0.65374211	2210.75	2092.6	2083.2	0.44920195	2087.90
1000	2184.4	2168.3	0.737044497	2176.35	2074.3	2074.1	0.009641807	2074.20
1500	2137	2142.3	0.248011231	2139.65	2017.9	2001.3	0.822637395	2009.60
2000	2089.5	2074	0.741804259	2081.75	1973.2	1967.4	0.29393878	1970.30
2500	2048.3	2049.3	0.048820973	2048.80	1928.6	1902.5	1.353313284	1915.55
3000	1997.2	2004.3	0.355497697	2000.75	1873	1793	4.271222637	1833.00